S&C FY02 ANNUAL REVIEW MEETING

DIAGNOSTICS AND CONTROL OF NATURAL GAS FIRED FURNACES VIA FLAME IMAGE ANALYSIS

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Project Description

- *Image analysis via machine vision and artificial intelligence techniques are used to obtain information from flame video images for diagnostics & control of gas fired furnaces. This includes guidance for balancing oxygen/fuel ratios between individual burners on multi-burner furnaces.*

- *Artificial Intelligence techniques are used to identify flame features that can be correlated with the oxygen/fuel ratio and other operational conditions such as flow rate changes in step or ramp-up fashion.*

Project Objectives/Goal

- ***IOF need(s) addressed by this technology***
  - *S & C Technology Area, subtopic "Sensors for Harsh Environment Applications"*
- ***Objectives***
  - *Macroscopic & Microscopic time varying Flame Image Analysis*
  - *Establish correlation between flame imagery & furnace control parameters for Multi-burner application*
  - *Improve diagnostic capabilities (detect burner malfunction)*
  - *Improve individual burner performance*
  - *Develop virtual temperature sensing capability*
- ***Overall goal***
  - *The goal is to provide guidance for balancing oxygen/fuel ratios between individual burners on multi-burner furnaces. Identifying and correcting fuel rich burners should result in improved fuel efficiency. It is anticipated that this system will offer great potential for improving furnace thermal efficiency and lowering NOx emissions.*

Technical Risks/Innovation

- ***Technical risks***
  - *Flame motion*
  - *One burner vs. multi-burner furnace*

- ***Innovation***
  - *Machine vision & AI techniques*

- ***Advancement of state-of-the-art; over competition***
  - *Color analysis & edge detection*
  - *Dynamic motion*
  - *Image analysis vs. spectrometry*

Task Performance

Past Technical Milestones

Milestone PHASE I	Due Date	Completion Date	Comments
▪ Equipment & Data Acquisition from pilot-scale glass furnace & natural gas research boiler	02/2001	02/2001	First year feasibility study
▪ Data analysis: – Image processing & Feature extraction – Image classification	02/2001	02/2001	

Task Performance

Past Technical Milestones

Milestone PHASE II	Due Date	Completion Date	Comments
▪ Data Acquisition and Evaluation from a Commercial Glass Furnace	3/31/01	3/16/01	
▪ Marketing Tool Development for Commercialization, ▪ Assessment of two AI Tools (DT & NN) for Pattern Recognition	6/30/01	6/30/01	
▪ Spectrometer Design Upgrade & Design of Experiments, and Virtual Temperature Sensing	9/30/01	9/30/01	
▪ Macroscopic versus Microscopic time varying Flame Image Analysis of both Pilot-Scale & Commercial Glass Furnace	12/31/01	12/31/01	
▪ Combustion Control Experimentation and Analysis under Step & Ramp-up Conditions at Pilot-Scale Glass Furnace	3/31/02	3/31/02	
▪ Combustion Control Experimentation under Ramp-up Condition and Various Oxygen/Fuel ratio at a Commercial Multi-burner Glass Furnace	6/30/02	5/28/02	Data analysis in progress

Progress Toward Performance Goals

Pilot Scale Glass Furnace

- *A 0.1-0.5 MMBtu/hr pilot-scale furnace that can melt from about 100 lbs of glass/day to 2,000 lbs of glass/day.*
- *Air-gas and oxy-fuel combustion.*
- *Furnace design allows different burner types and burner arrangements, and positioning.*
- *Furnace is controlled using Labview hardware and software control system.*

Progress Toward Performance Goals

Experimentation at the Pilot Scale Glass Facility

- *The oxygen/fuel ratio was varied from 1.8 to 2.4*
- *Various combustion control experimentation in step & ramp-up fashion*
- *To install the spectrometer lens (and the attached fiber optics) inside the harsh environment of the furnace, a water/air-cooled case was designed and fabricated at a local machine shop*

Equipment Setup at The Pilot-scale Glass Furnace

(a)

(b)

(c)

(a) Camera and flue gas equipment,

(b) Spectrometer and computer,

(c) Water/Air-cooled spectrometer mounting setup.

Progress Toward Performance Goals

Virtual Temperature Sensing

- *Virtual temperature sensing is accomplished by two different methods*
  - *best fit approach*
  - *intensity ratio approach*

Progress Toward Performance Goals

- *Method 1: Best Fit Approach*

  This approach is based on the assumption that the measured spectrum is a composite of two blackbody profiles at different temperatures T1 and T2 plus a constant background. Temperature T1 represents the hot combustion gases and T2 the wall temperature as represented in the following equation:

η_{spec} : calculated efficiency of the spectrometer grating and optical cable

A: correction factor, I: intensity, λ: wavelength, T: temperature,

h: Planck'sconstant, k: Boltzmann constant

$$I_{bb,meas}(\lambda) = A\eta_{spec}\left(E_{\lambda,bb}(\lambda,T_1) + E_{\lambda,bb}(\lambda,T_2)\right)$$

$$E_{\lambda,bb} = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda\kappa T}} - 1\right)}$$

Progress Toward Performance Goals

- *Method 2: Intensity Ratio Approach*

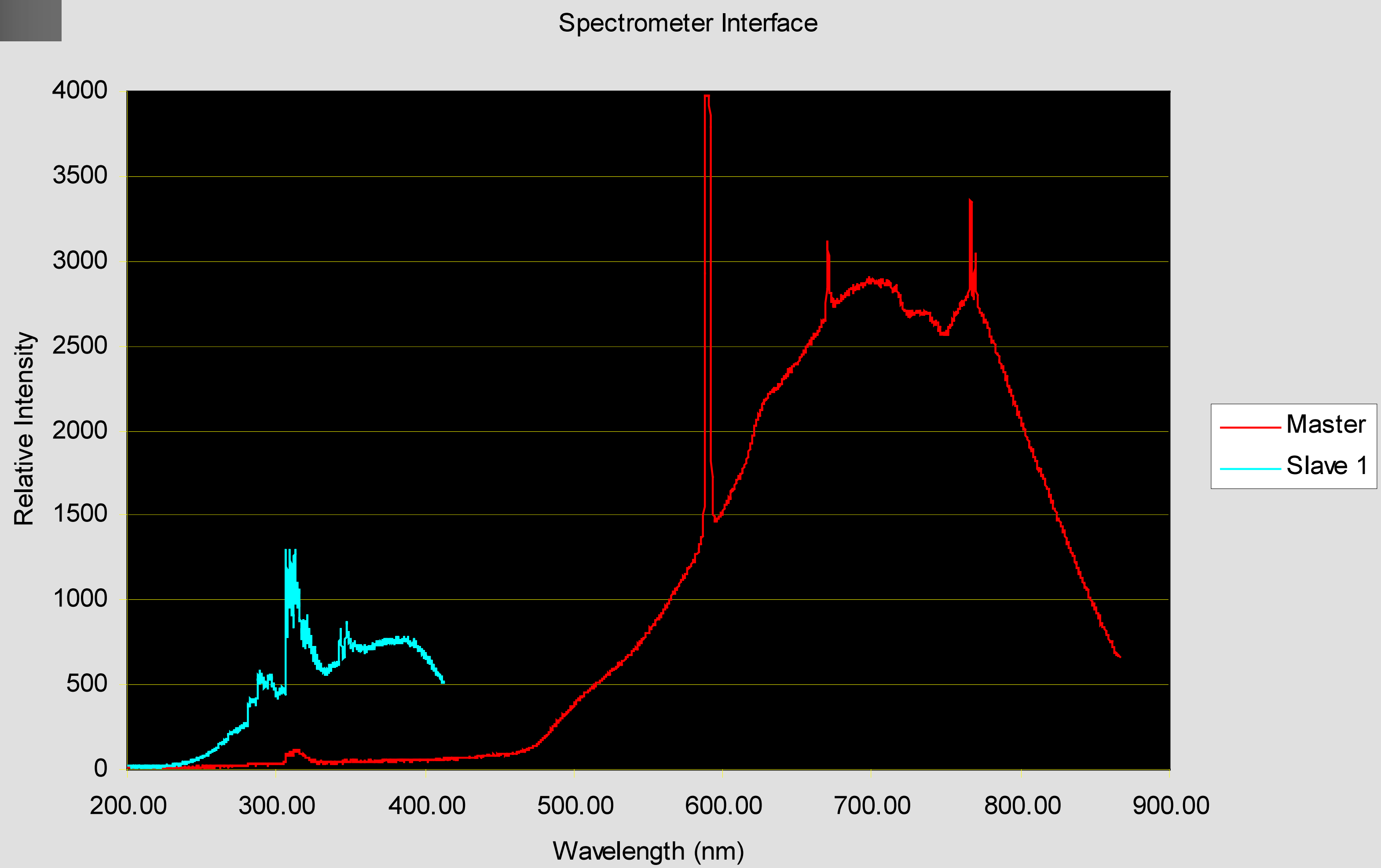
  This approach is based on ratio of intensities of paired wavelengths along a selected spectrum:

$$A\, I_1\lambda_1^5 / I_2\lambda_2^5 = (e^{(hc/\lambda_2 KT)} - 1) / (e^{(hc/\lambda_1 KT)} - 1)$$

Calculated temperatures vs. O/F ratios

Temp (K)	NG (scfh)	O/F
1726	110	2.1
1722	110	1.8
1803	140	1.8
1707	80	2.1
1762	110	2.1
1749	140	2.1
1684	80	2.4
1727	110	2.4
1824	140	2.4
1699	96	2.4
1736	110	2.1
1757	128	1.8

Pilot Scale Glass Furnace



A sample plot of both UV and VI spectrum

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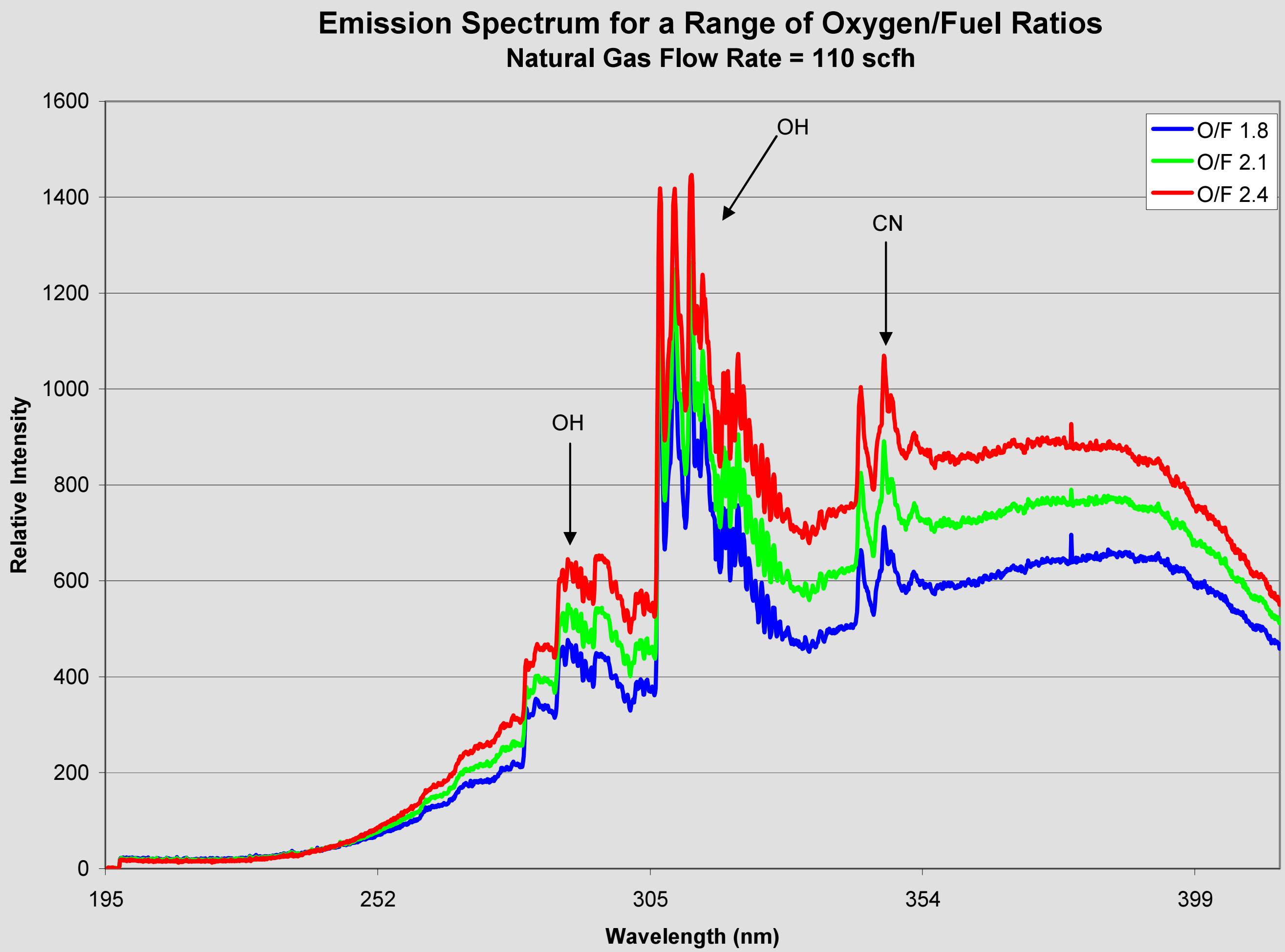
Pilot Scale Glass Furnace



Emission spectrum in the 200-400 nm range

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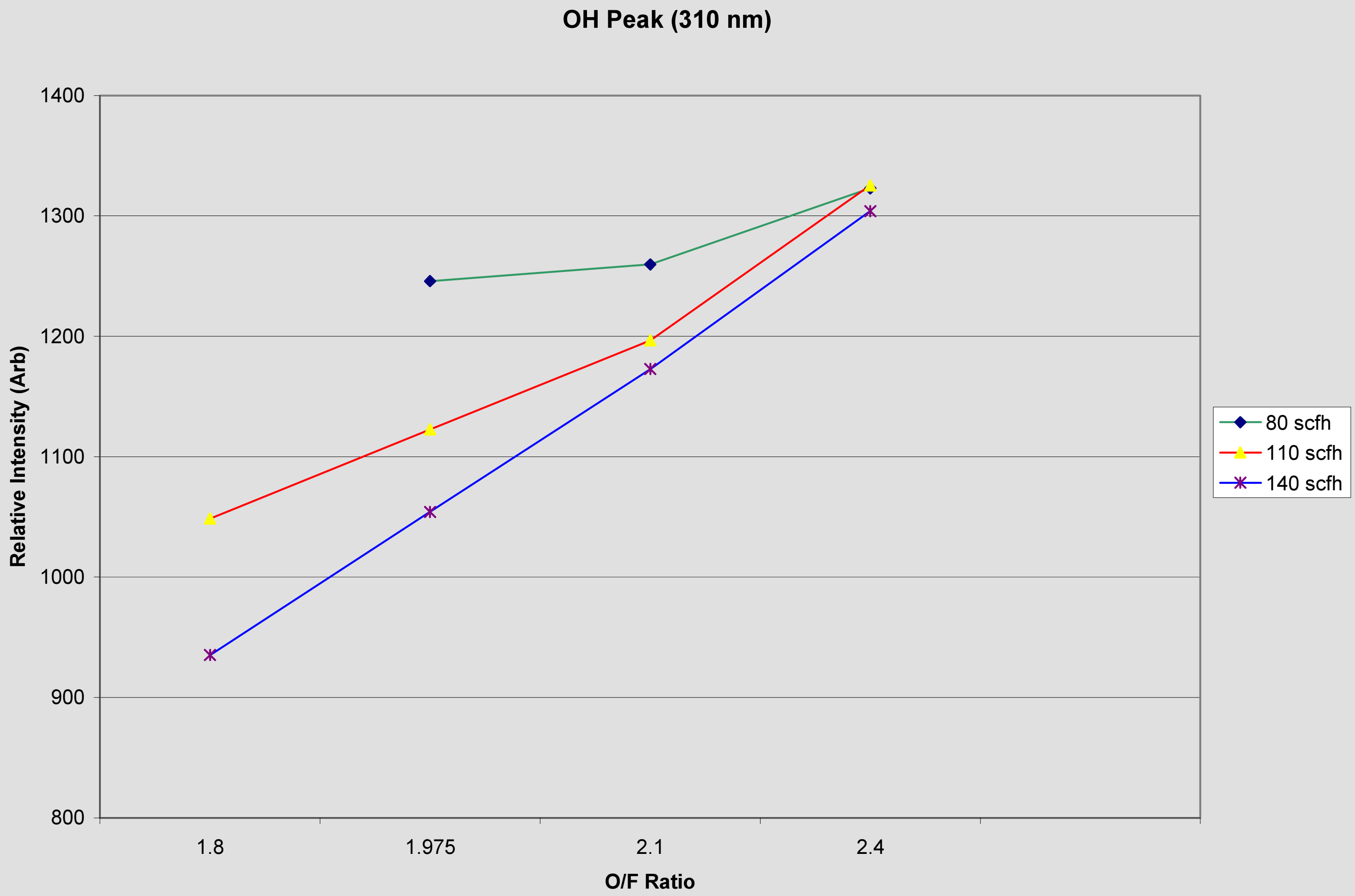
Pilot Scale Glass Furnace



OH radical spectrum intensity variation with O/F ratio

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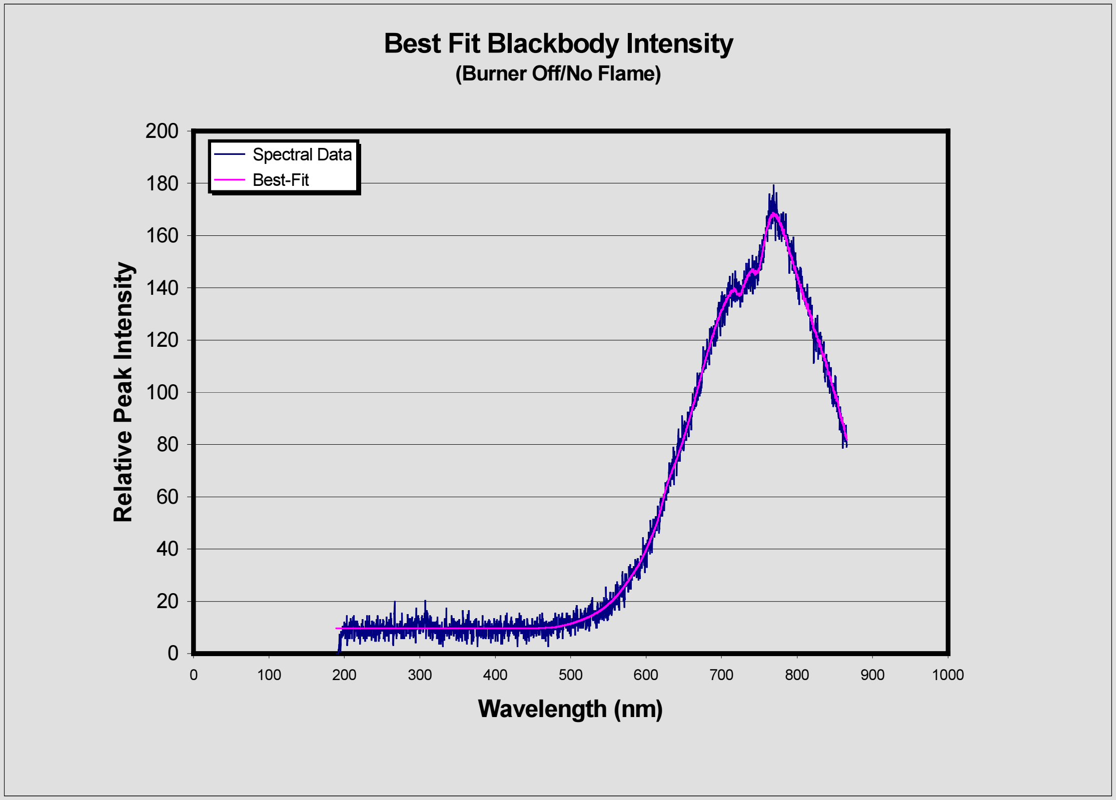
Pilot Scale Glass Furnace



Plot of measured and best-fit spectra with no flame condition

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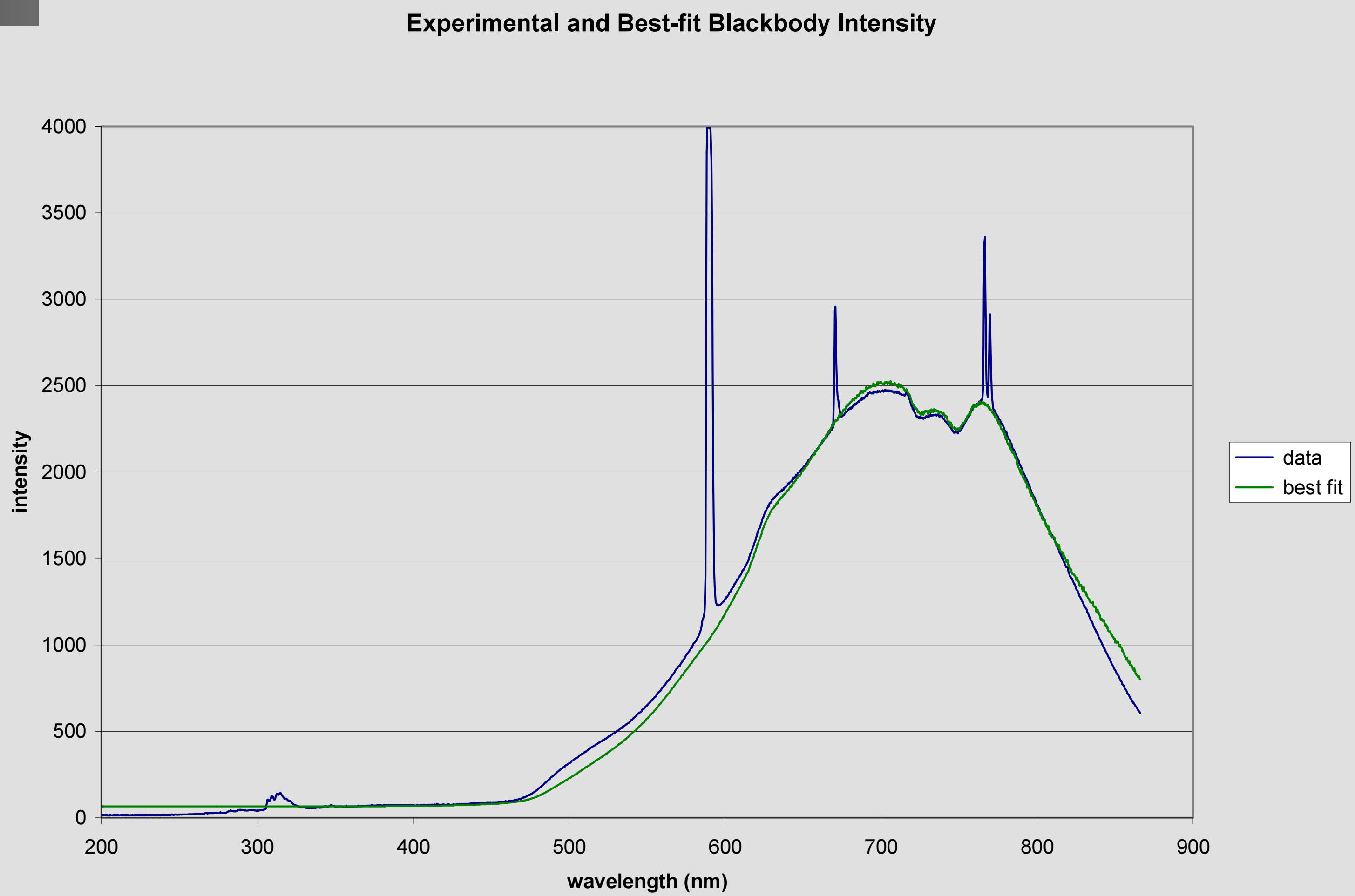
Pilot Scale Glass Furnace



Spectral data and best-fit blackbody trace for VI region

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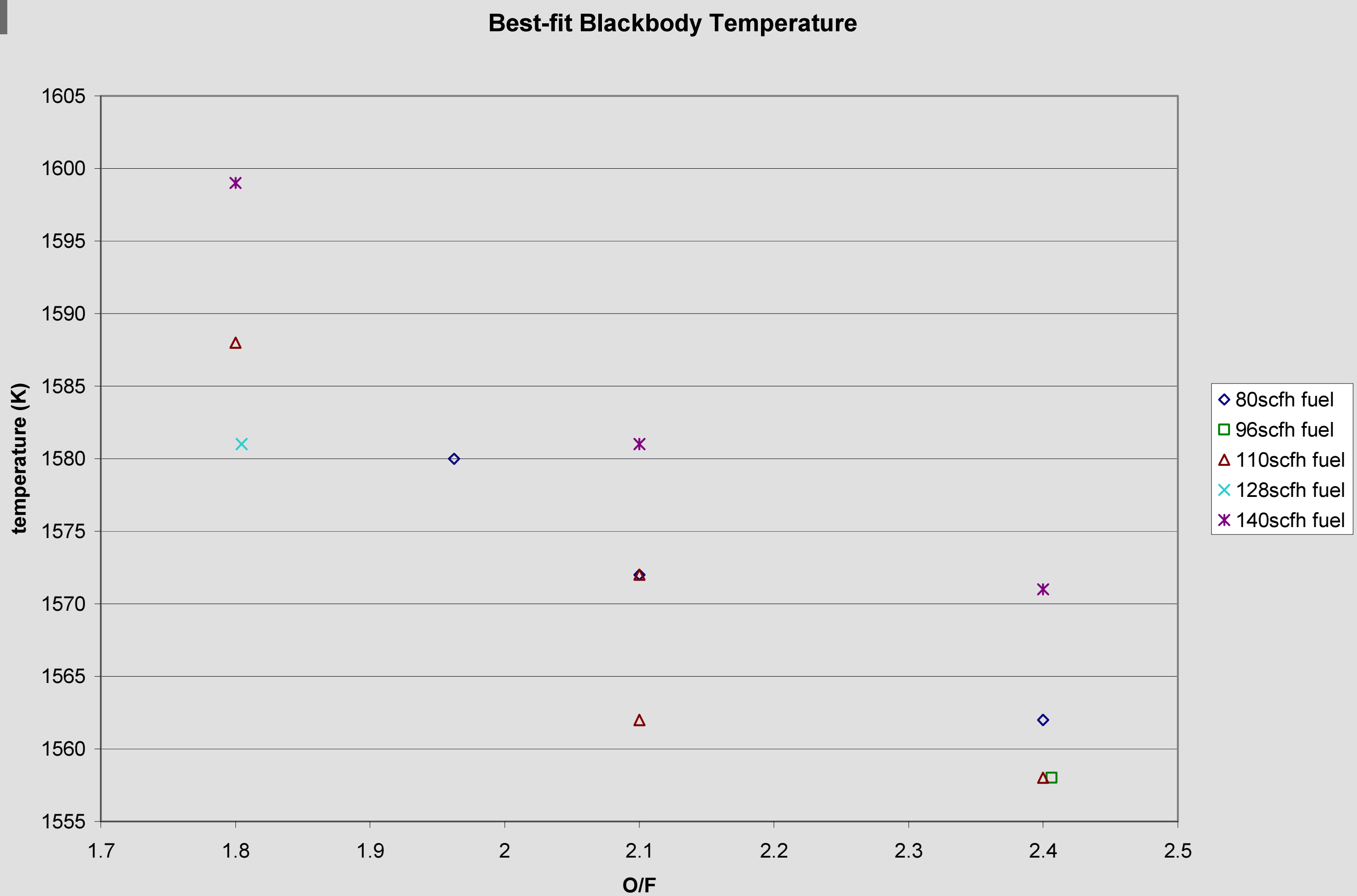
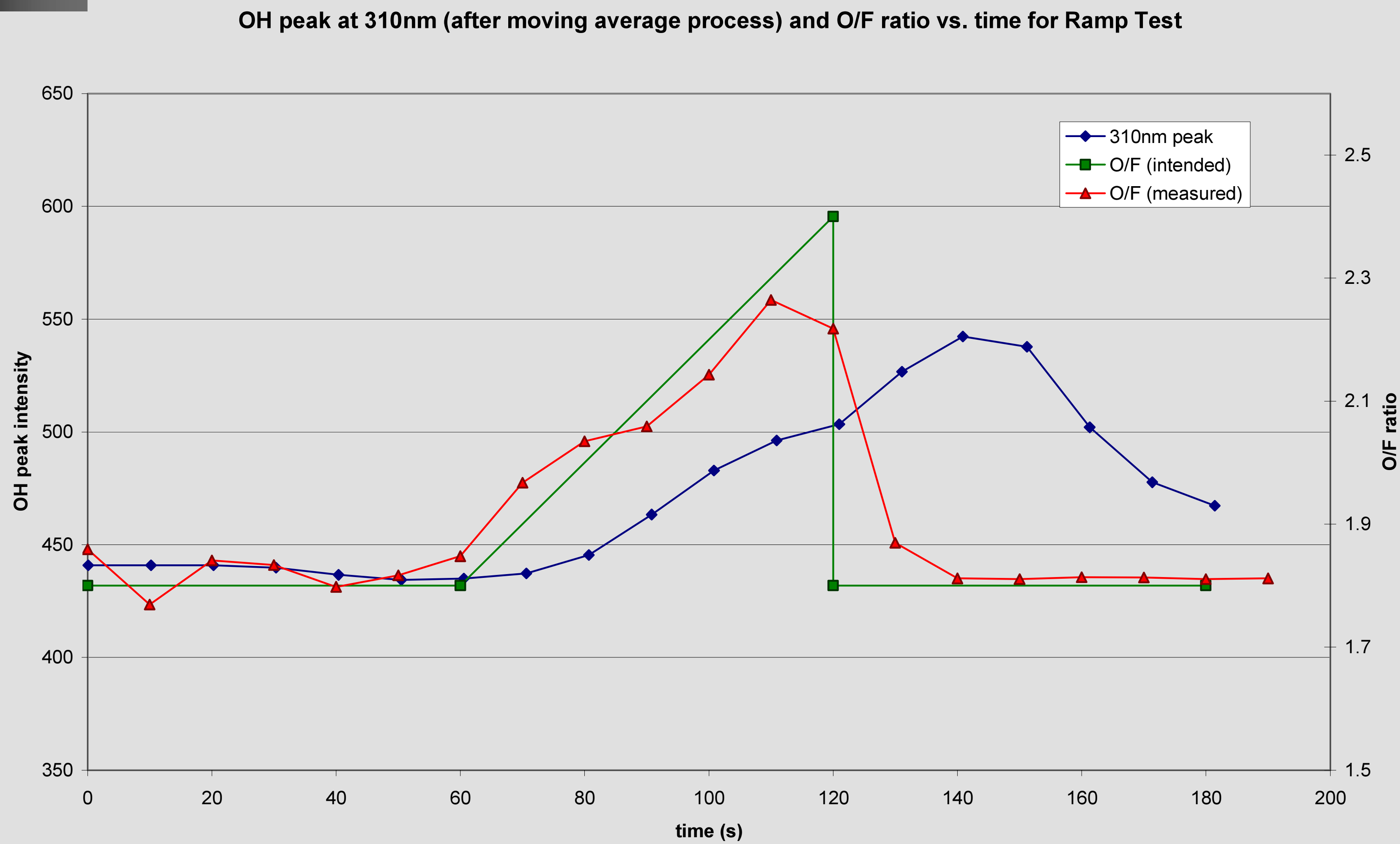
Pilot Scale Glass Furnace



Calculated temperature as a function of the oxygen/fuel ratio

Control Experimentations at the Pilot-Scale Furnace



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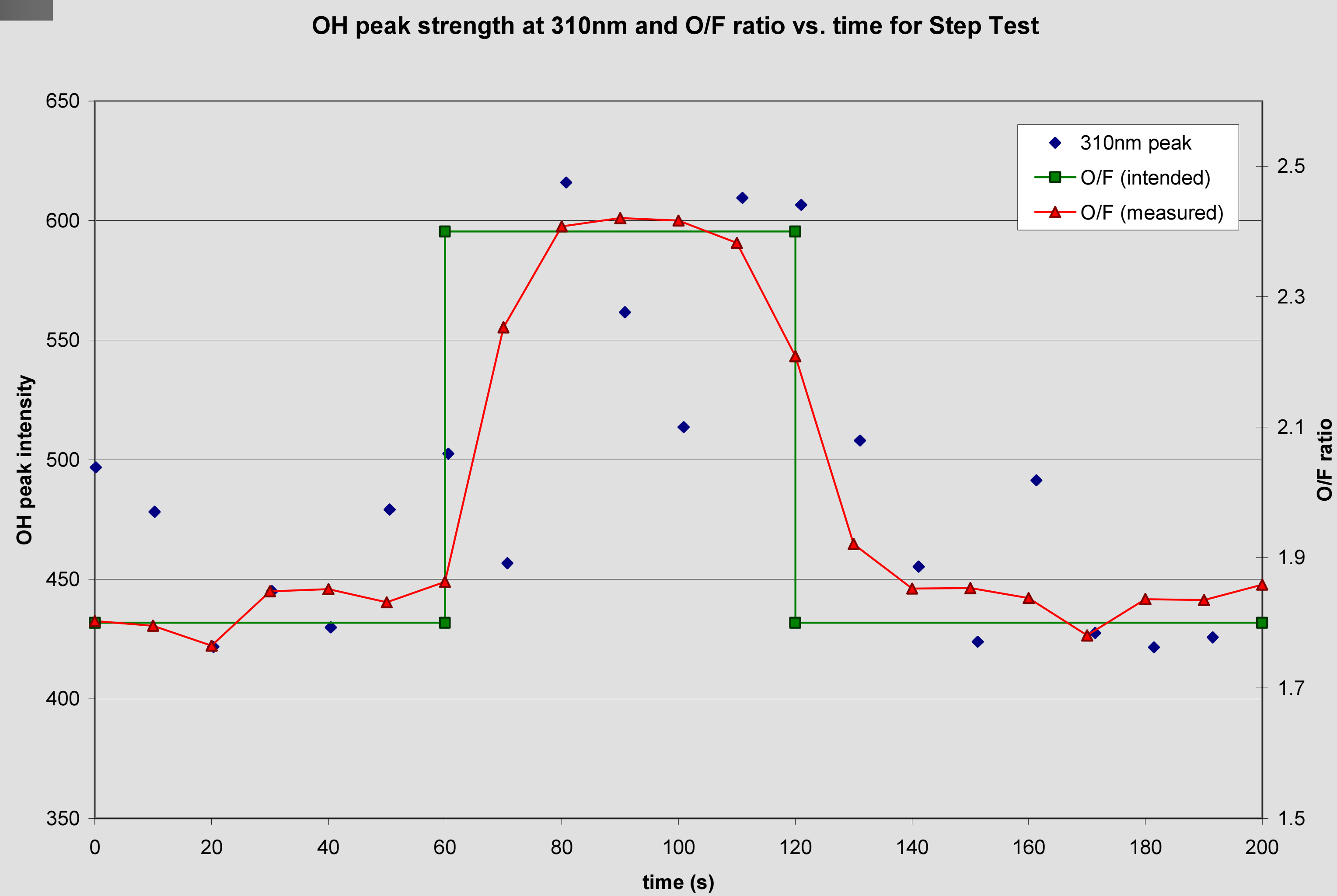
Control Experimentations at the Pilot-Scale Furnace



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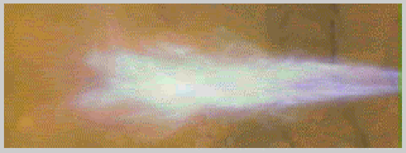
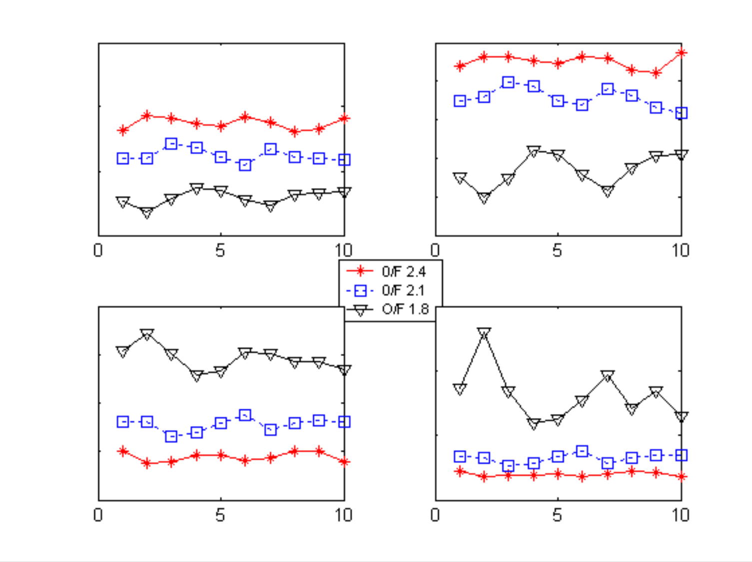
Flame Images from the Pilot Scale Glass Furnace



(a) (b) (c)

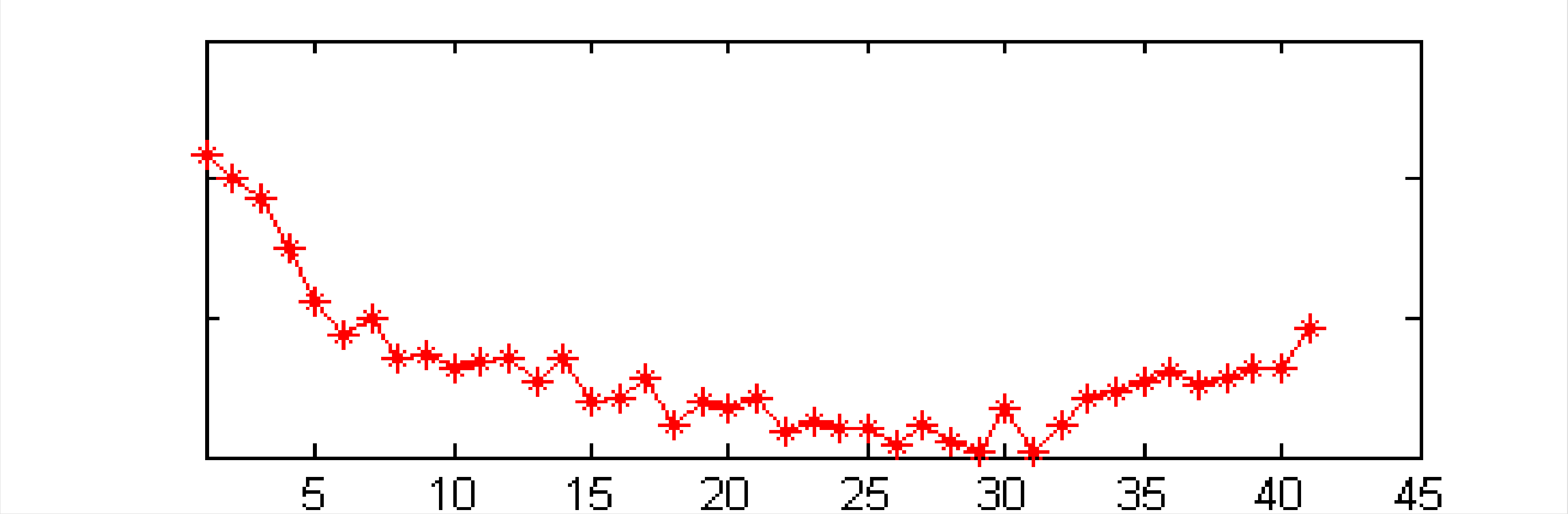
Flame images at (a) 2.4 O/F ratio, (b) 2.1 O/F ratio, c) 1.8 O/F ratio



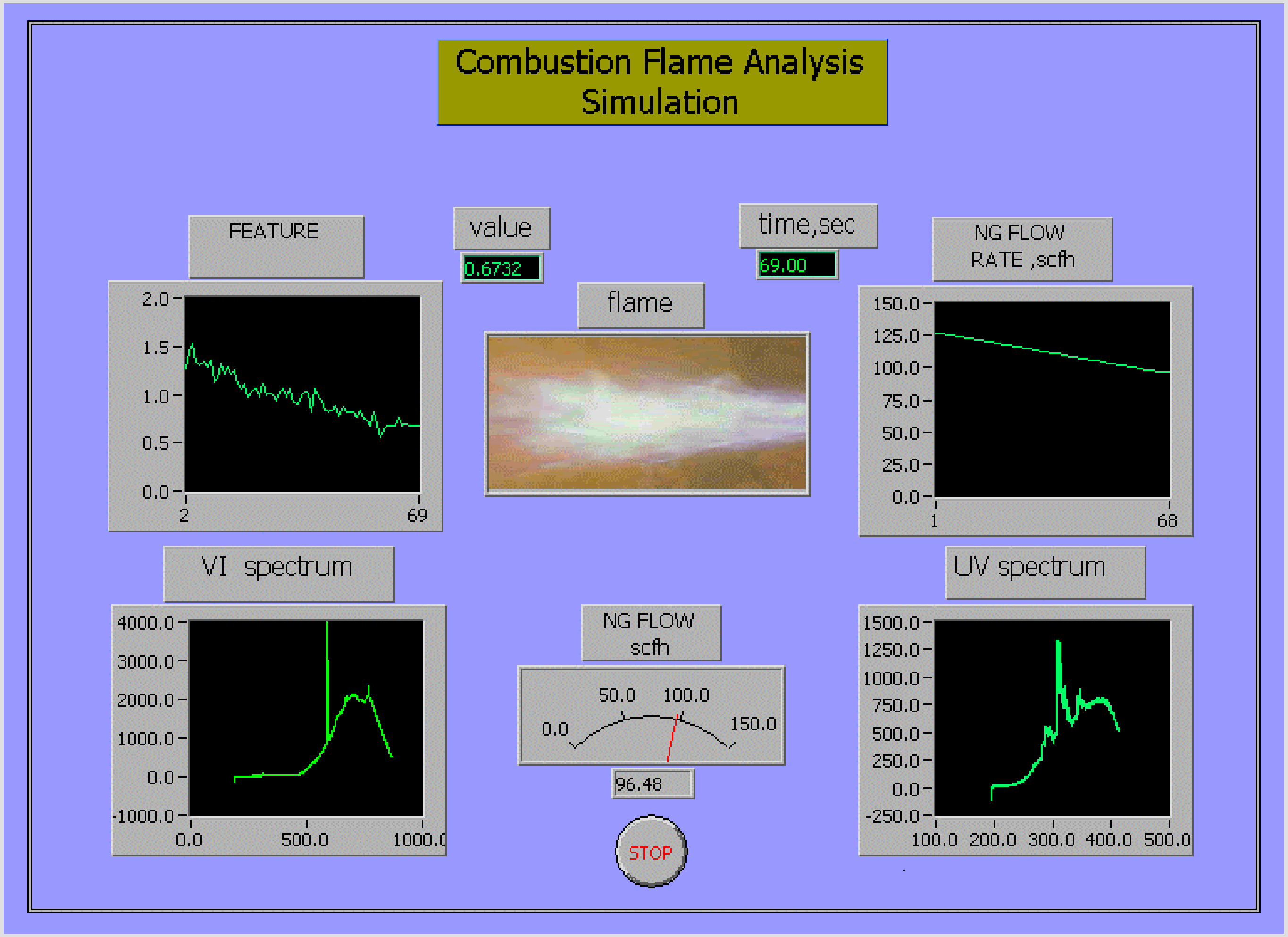
10-second macroscopic behavior of the flame features at various O/F ratios

Control Experimentations at the Pilot-Scale Furnace

- *Sample feature generated from 30 second image data of a step-down experiment*
- *Experiment followed by ten second (data points from 31 to 41 in the plot) Feature data of the step-up experiment*



Control Experimentations at the Pilot-Scale Furnace



Screen picture of Labview control simulation

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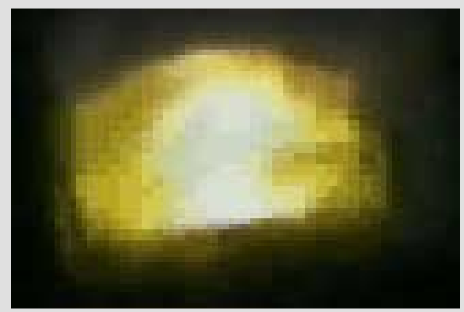
Commercial Glass Furnace (two-burner)

- *End-fired furnace with regenerative heat recovery*
- *Combustion Tec side-fired burners*
- *The nominal production throughput of each furnace is approximately 105-110 U.S. tons per day*

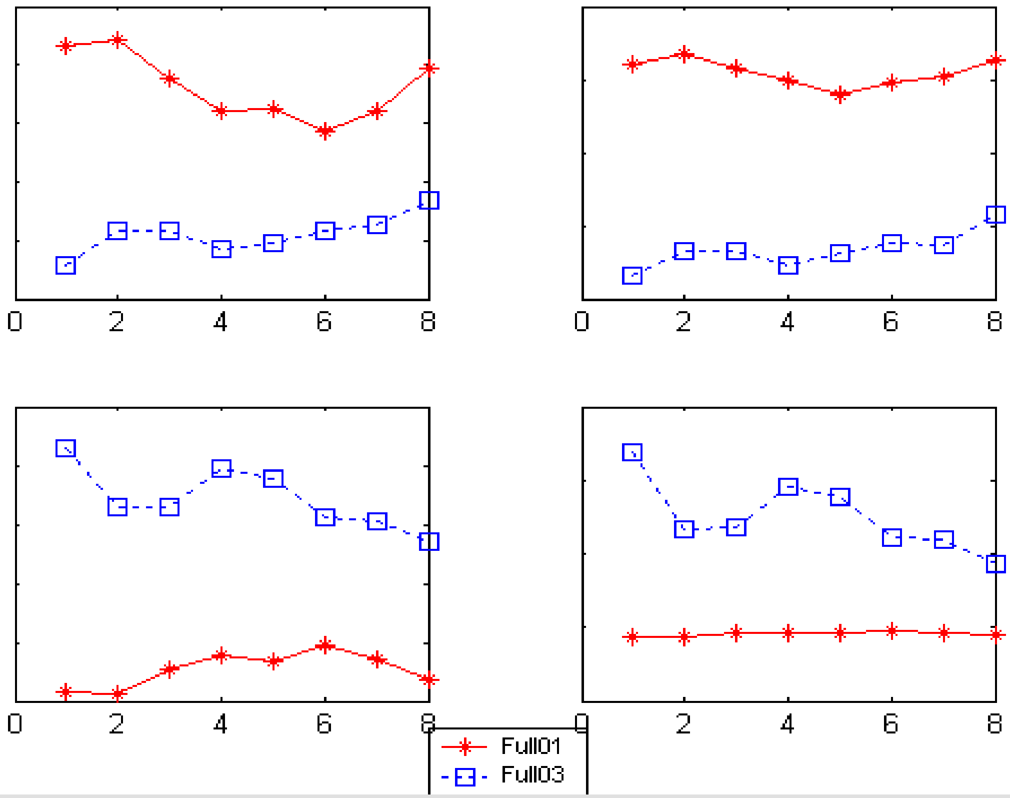
(a)



(b)

Sample images: a) side view, and b) back view

Commercial Glass Furnace (two-burner)



Features showing two firing rate conditions

The "full 01" data represent lower firing rate

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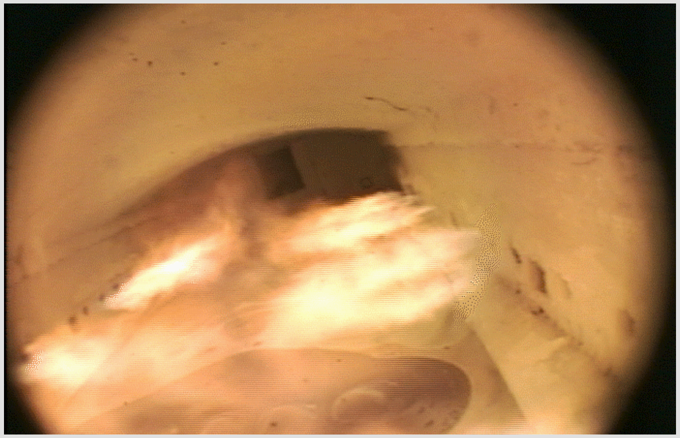
Commercial Glass Furnace (multi-burner)

- *Fiber glass manufacturing furnace*
- *7 pairs of individually O/F ratio controlled burners*
- *13 million Btu/hr*



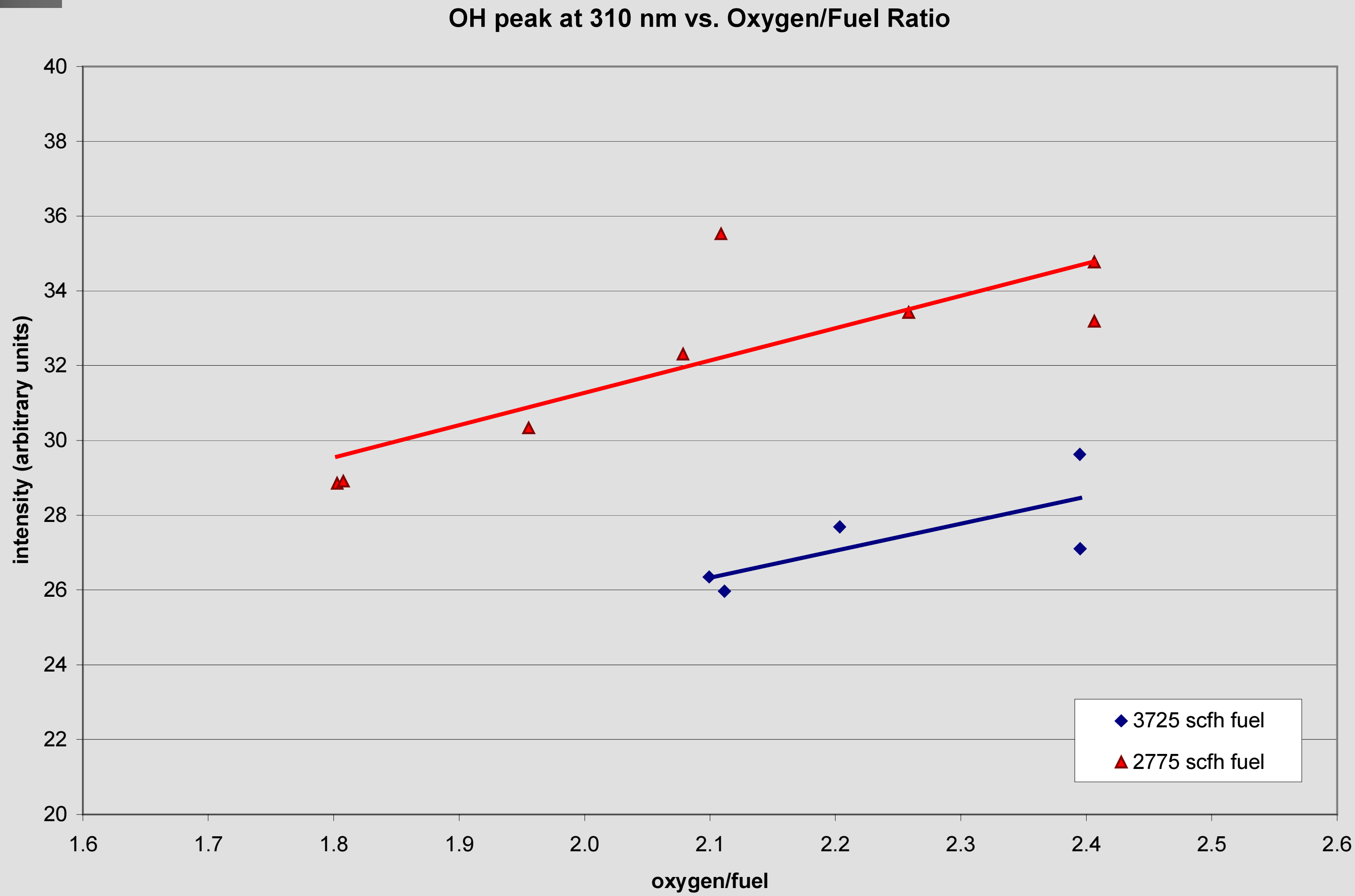
Commercial Glass Furnace (multi-burner)

Camera and Water/Air-cooled spectrometer mounting setup



Sample flame

Commercial Glass Furnace (multi-burner)



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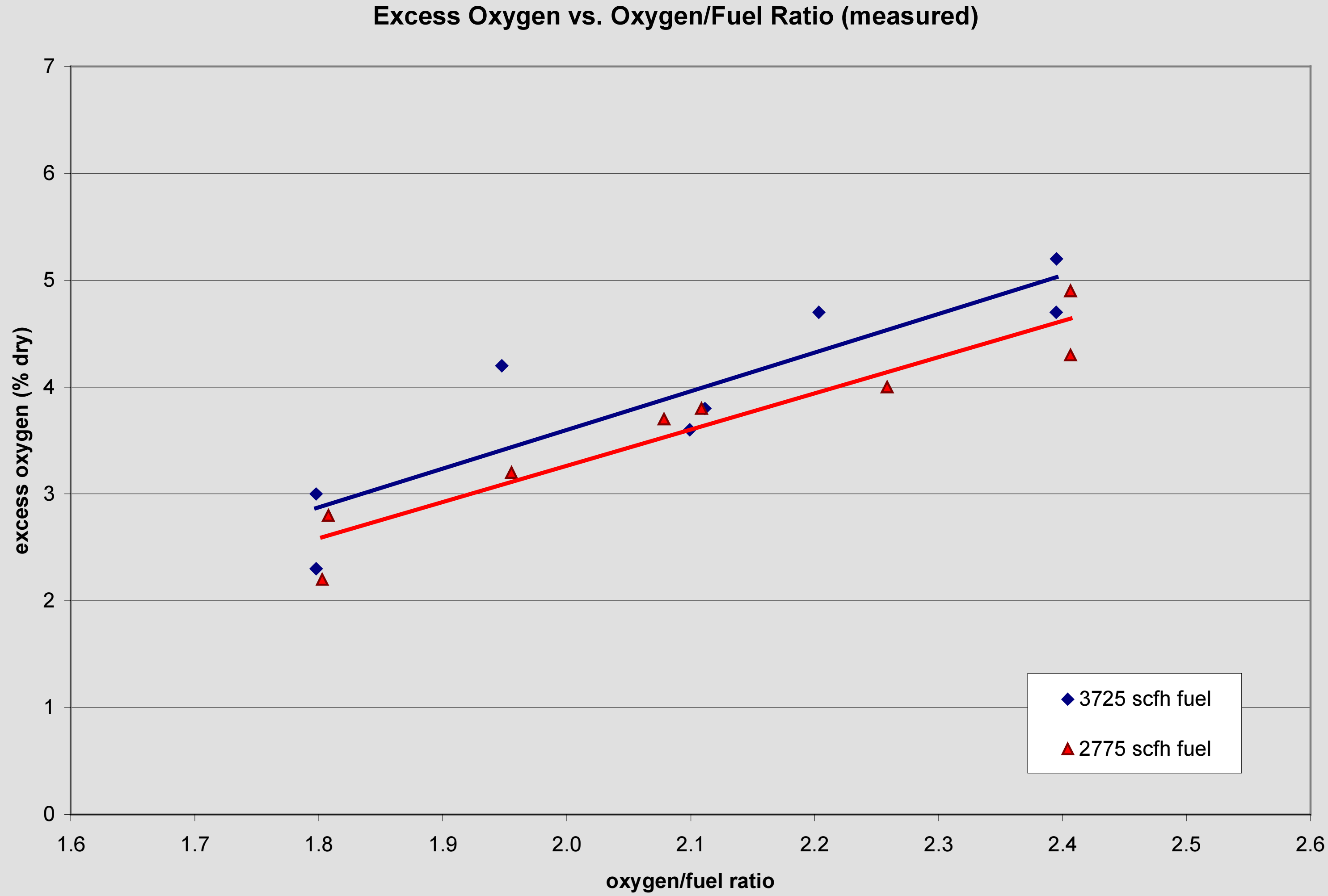
Commercial Glass Furnace (multi-burner)



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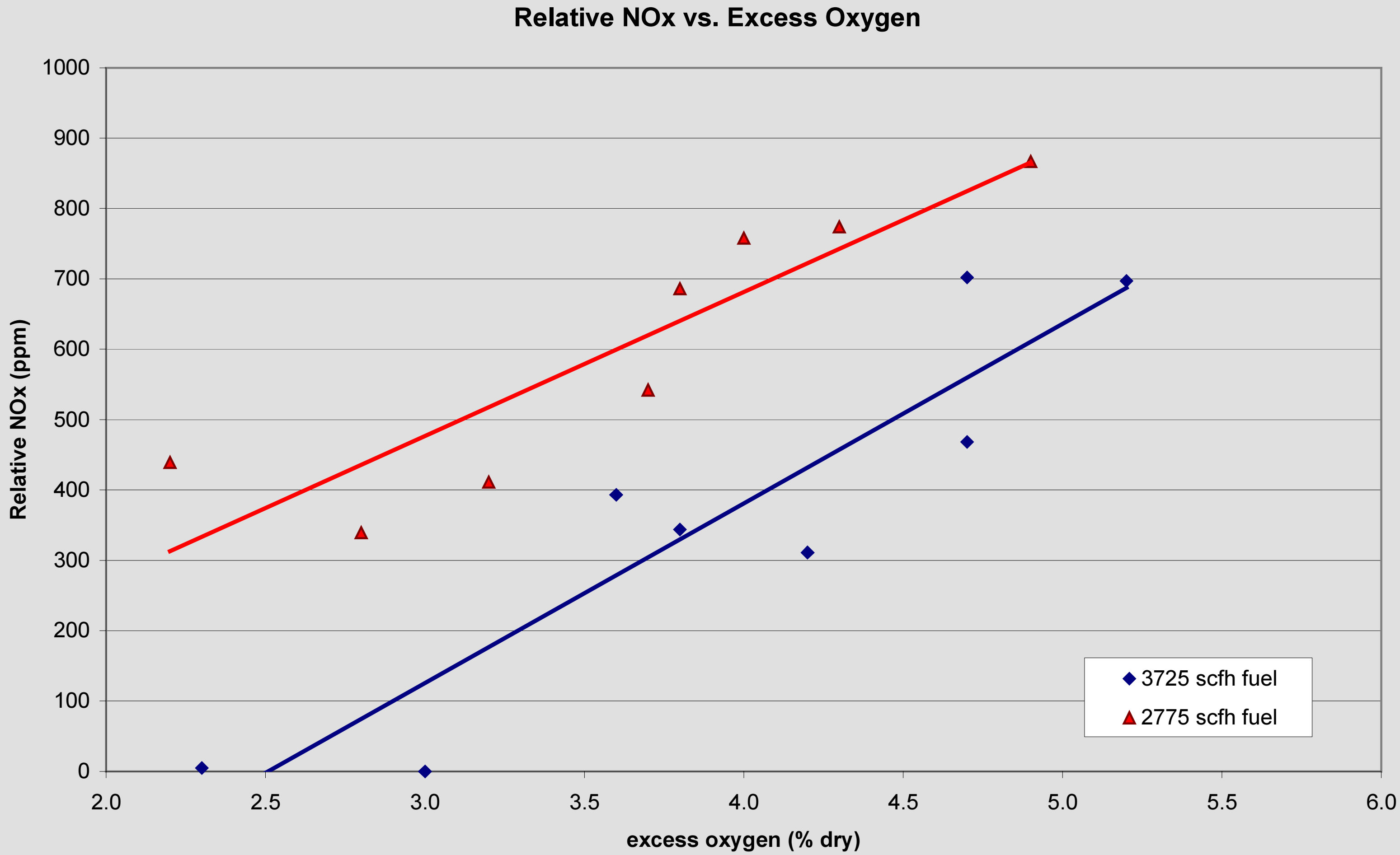
Commercial Glass Furnace (multi-burner)



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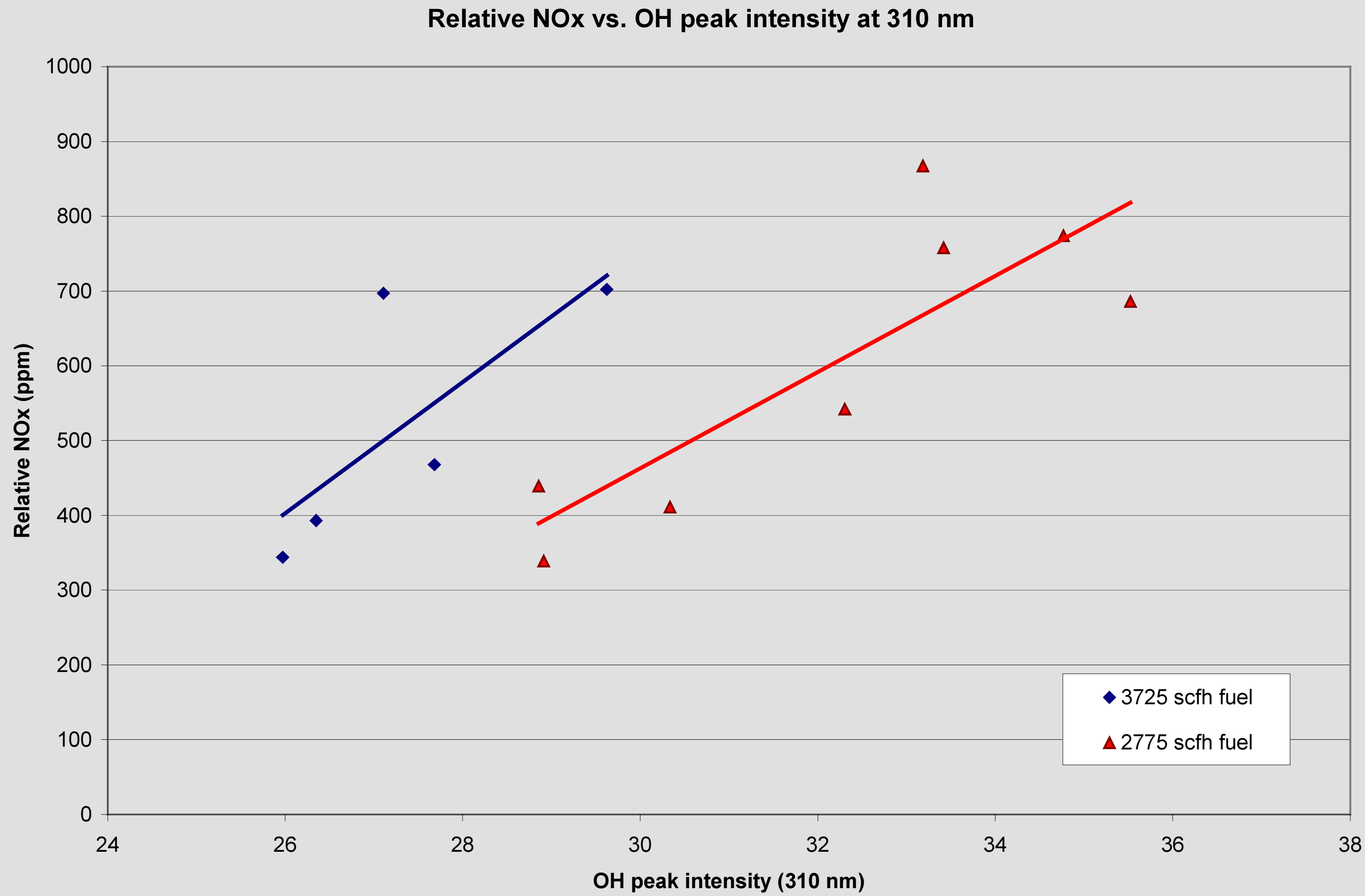
Commercial Glass Furnace (multi-burner)



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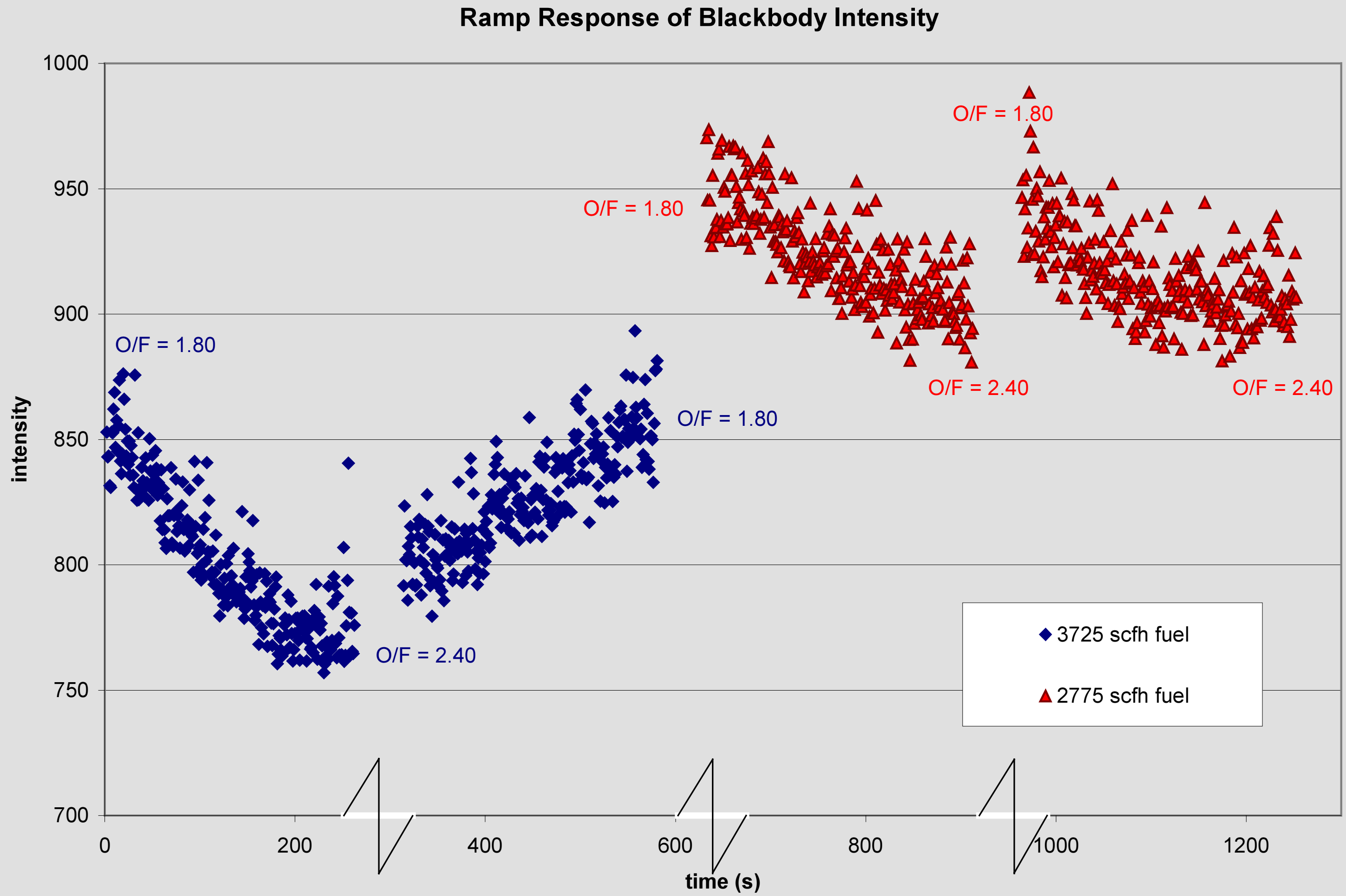
Commercial Glass Furnace (multi-burner)



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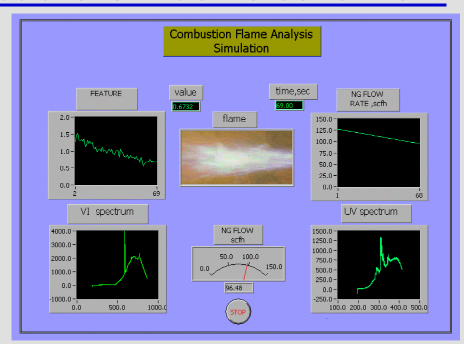
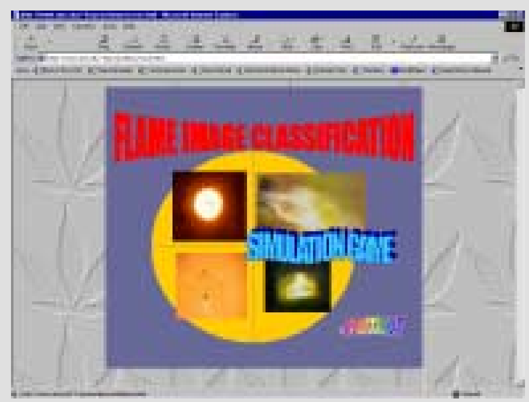
Commercialization

- ***Proposed plant tests/deployments, and planned use in IOF manufacturing plant(s)***
  - *Glass manufacturing:*
  - *Multi-burner furnace*
  - *Two-burner furnace*
- ***Commercialization path & partners***
  - *Distributed Commercialization*
  - *industry Cooperation*
  - *Marketing tools: Presentation & Simulations*

    [*http://www.missouri.edu/~keyvans/publichtml/demo/cover.html*](http://www.missouri.edu/~keyvans/publichtml/demo/cover.html)





Performance Merits

- ***Improving energy efficiency***
  - *How will energy be saved?*
    - *Improved efficiency as a result of improved combustion*
  - *What are the energy savings (per installed unit and nationwide)?*
    - *35 billion Btu/yr per unit installed based on 5% efficiency improvement*
    - *175 billion Btu/yr nationwide based on 5 installation annually*

Performance Merits

- ***Reducing emissions***
  - *How will emissions be reduced?*
    - *burner balancing at optimal conditions allows operation at reduced excess air (oxygen) levels resulting in improved thermal efficiencies and reduced emissions*
  - *What are the reduction levels?*
    - *5% to 30%*

Performance Merits

- ***Improving product quality***
  - *How will product quality be improved?*
    - *By preventing disruptions in production that can lead to quality problems such as seeds, stones, and striae. Often less than optimal flame conditions cause seeds by oxidation/reduction reactions with the glass melt, or by disrupting convective flow patterns in the actual glass melt that are sensitive to combustion conditions. These flow patterns are essential to removal of bubbles from the glass and can be altered by small changes in combustion conditions throughout the furnace.*
    - *Flame impingement on walls can cause serious degradation of furnace refractory brick causing insoluble stony inclusions to enter the glass melt. Some of these inclusions may partially melt leading to striae that appear as knots or cords of glass with a different index of refraction from the base composition.*
  - *How will this improvement be quantified?*
    - *Statistical data before and after implementation of the flame monitoring system are needed for quantification of quality improvement.*

Performance Merits

- ***Reducing costs***
  - *How will costs be reduced?*
    - *By extension of refractory life and associated savings as a result of proactively correcting damaging conditions*
    - *By saving energy as a result of improved efficiency*
  - *What are the cost savings?*
    - *$210,000/yr based on 80 MMBtu/hr furnace and 5% energy saving*

Path Forward

Future Technical Milestones

Milestone	Due Date	Completion Date	Comments
Multiburner commercial furnace data analysis	9/30/02	In progress	
Prototype development/ Software Packaging	2/15/03		
Graphical Display Design	2/15/03		
Data acquisition & analysis from Air/fuel pilot-scale furnace			Scheduled for July 2002
Data acquisition & analysis from an aluminum furnace	2/15/03		

Path Forward

- ***Next steps***

  Develop business plan for distributed commercialization

  Complete multi-burner data analysis & develop the prototype

  Design the graphical display

- ***Go/no-go consideration(s)***

  N/A